Search for high-spin isomeric states in the rare-earth region

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SEARCH FOR HIGH-SPIN ISOMERIC STATES IN THE RARE-EARTH REGION

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Several new high-spin ($I > 10$) isomeric states in the mass region $A = 144-164$ are located in a systematic search with ^{12}C induced reactions, employing a sixteen NaI (Tl) – Ge (Li) detector multiplicity filter. The proximity to the $N = 82$ neutron shell closure strongly suggests that shell effects contribute significantly to this isomerism.

The study of high-spin isomeric states is triggered by the interest in the interplay between collective excitations and single particle degrees of freedom. The possible occurrence of such states has been suggested theoretically [1,2] in a region of high angular momentum where shell structures disturb the collective excitations. Isomeric states with $I > 10$ have already been known for a long time e.g. near the $Z = 82, N = 126$ closed shells. The structure of these states has been explained on the basis of pure quasi-particle configurations [3,4]. Recent calculations on this subject [5–8] show that at least two categories of high-spin isomers can be found in medium-mass and heavy nuclei. The first class of isomers occurs in nearly spherical nuclei with a few nucleons outside closed shells, where shell-structure effects may generate an irregular yrast line. Some states on the yrast line become "yrast traps" when their decay is only possible through high-multipolarity transitions or by non-collective many-particle transitions [5]. Experimental evidence for the shell structure of isomers in this region has been found in several Gd isotopes [9]. The second category of isomers is characterized by angular momenta $I > 40$ and strong oblate ($\beta \approx 0.4$) deformations [2]. In contrast to the first category the second one is not restricted to the vicinity of closed shells. Recently many isomers with multiplicities of the delayed γ-rays between 8 and 20 were reported to originate from compound nuclear systems located on an "island" beyond $N = 82$ by the Copenhagen–Darmstadt collaboration [10] in a broad search for high-spin isomeric states. A detailed comparison between this experimental information and the theoretical calculations is not possible due to the fact that the final nuclei were not determined and due to the lack of information on the spin and excitation energy of the isomeric states.

In this letter we report on a search for high-spin (presently defined as $I > 10$) isomeric states in the region with $Z = 62-70, N = 82-92$: We have identified several new isomers in nuclei near the $N = 82$ closed shell, measured their half-lives and estimated spins and excitation energies on the basis of measured excitations functions, γ-ray energies and multiplicities. Targets of ^{139}La, ^{141}Pr, $^{142,144,146}Nd$, $^{144,148,149,150}Sm$ and $^{152,154}Gd$ were bombarded with 70, 80, 101 and 120 MeV ^{12}C beams from the 280 cm AVF cyclotron in Groningen. We have studied 26 beam–target combinations and in this way excited about 50 final nuclei. In these experiments γ-ray cascades were detected with a 110 cm^3 Ge (Li) detector and a sixteen 7.5 × 5.0 cm^2 NaI (Tl) detector-multiplicity filter, both prompt and delayed with respect to the beam burst. The timing properties of the present set-up restricted the observation of isomers to those with $t_{1/2} > 5$ ns. Half-lives could be determined in the range 10–500 ns. The electronic system was designed to record the γ-ray energy and time signals and up to sixteen-fold coincidences between the Ge(Li) and NaI (Tl) detectors. An example of the timing technique is given in fig. 1 where the decay of the isomeric states in ^{153}Er and probably in ^{152}Ho is separated from the prompt

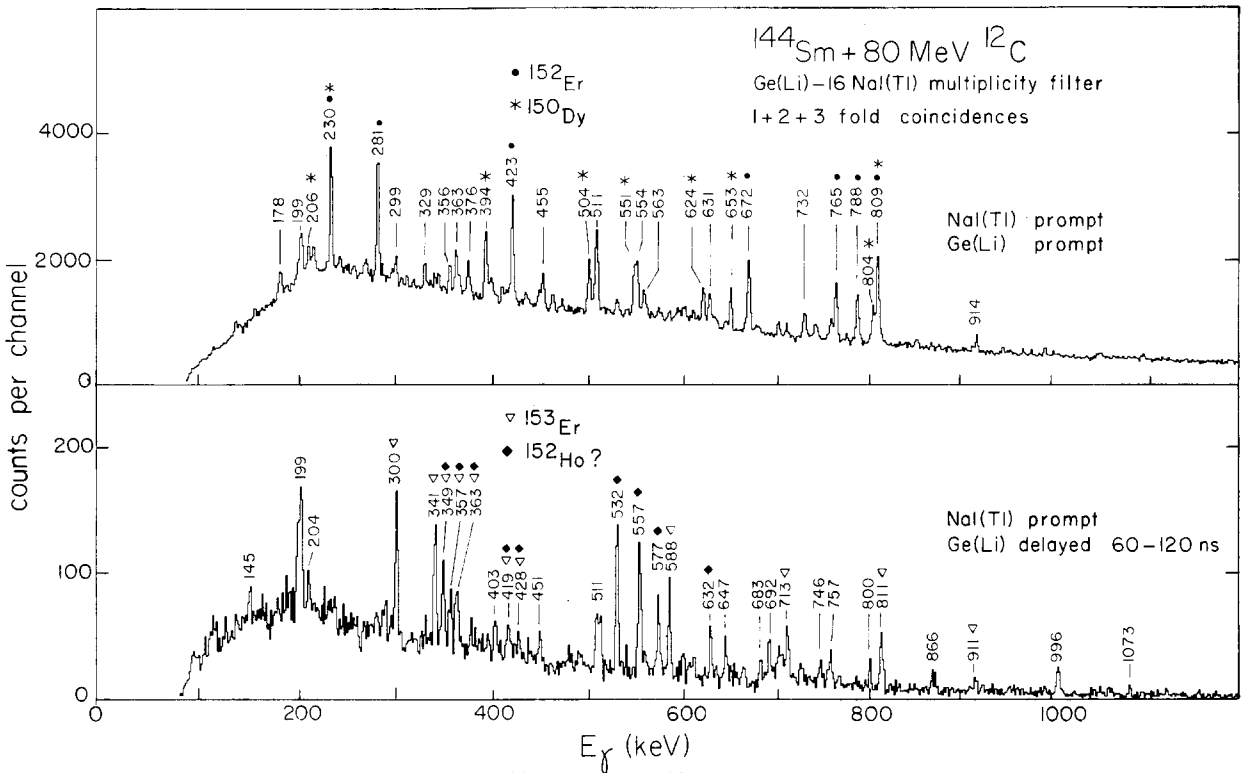

Fig. 1. Gamma-ray spectra observed in the reaction ^{144}Sm + 80 MeV ^{12}C with a Ge (Li) detector in coincidence with one, two and three NaI (Tl) detectors.

γ-ray transitions in ^{152}Er and ^{150}Dy, all observed in the reaction ^{144}Sm + 80 MeV ^{12}C. The identification of the final reaction products was based on measurements of their radioactive decay, on known γ-ray transitions and on comparisons between experimental excitations functions and hybrid-model calculations. The latter method could be verified and adjusted using the information on reactions with well-known final nuclei. By gating on all delayed γ-rays observed in the Ge (Li) energy spectrum, time spectra were obtained for all identified isomers.

The mean multiplicity $\bar{M}_D$ of the delayed γ-ray cascade deexciting an isomer was determined from the 0–6 fold coincidences between delayed γ-rays in the Ge (Li) and NaI (Tl) detectors. The excitation energies of the isomeric states were determined using the mean multiplicities of the delayed γ-rays and their mean energies as: $E_x = \bar{M}_D \times \bar{E}_{\gamma D}$. The mean γ-ray energy $\bar{E}_{\gamma D}$ was determined in each case from the delayed NaI (Tl) γ-ray spectra obtained in coincidence with delayed γ-ray transitions observed in the Ge (Li) detector. The NaI (Tl) spectra were unfolded using the experimentally determined response functions and efficiency curve. For the known 60 ns isomer in ^{152}Dy we have determined the excitation energy as 5.3 ± 0.7 MeV from $\bar{M}_D = 7.5 \pm 0.5$ and $\bar{E}_{\gamma D} = 710 +$ 80 keV in good agreement with the reported [11] value $E_x = 5.03$ MeV. Lower and upper limits for the spins of isomeric states have been obtained by assuming that their decay proceeds through either 50% stretched dipole and 50% stretched quadrupole transitions or through 100% stretched quadrupole transitions, respectively. The upper limit is enlarged by two units to account for the presence of a possible E3 transition. These assumptions are based on the known decay schemes of the isomers in ^{146,147}Gd, ^{148,149,152}Dy and ^{154}Er. Since in all these nuclei the isomeric decay proceeds almost entirely through stretched E2 transition these limits (see table 1) can be considered as conservative.

All nuclei in which low- and high-spin isomeric states were oserved in this experiment are indicated

Table 1
Properties of the new high-spin isomeric states, observed in the present experiment

Final nucleus	E_γ (keV) delayed transitions	$T_{1/2}$(ns)	$\bar{M}_D$	E_X(MeV) a)	I b)
^{149}Dy	200, 239, 255, 270, 429, 489, 740, 984, 1006, 1232, 1335.	29 ± 3	7.5 ± 0.5	6.9 ± 0.8	47/2–63/2
^{151}Dy	163, 265, 345, 355, 408, 435, 468, 527, 570, 649, 653, 736, 775, 822, 838, 878.	18 ± 4	11.0 ± 0.5	6.2 ± 0.6	39/2–57/2
^{150}Ho, ^{150}Er	226, 263, 280, 314, 628, 1096.	100 ± 30	6.0 ± 1.0	4.2 ± 0.8	$\frac{I^*}{8-16}$
	305, 712, 726.	50 ± 20	6.0 ± 2.0	5.0 ± 1.5	6–18
^{152}Ho?	532, 557, 577, 632.	90 ± 40	5.5 ± 0.5	3.7 ± 0.5	8–14
^{152}Ho, ^{153}Er	349, 357, 363, 419, 428, 746, 911.	> 200	5.5 ± 0.5	2.8 ± 0.5c)	8–14
^{153}Er	300, 341, 588, 713, 811.	500 ± 300	5.0 ± 0.5	3.2 ± 0.4	7–13

a) $E_X = \bar{E}_{\gamma D} \times \bar{M}_D$, see text.
b) Spin limits given by $1.5\ \bar{M}_D \leq I - I_0 \leq 2\bar{M}_D + 2$, where I_0 is the spin of the ground state or that of a lower isomeric state. For ^{150}Ho, ^{152}Ho and ^{153}Er $I^* = I - I_0$ is given, because I_0 is unknown.
c) This isomer lies probably on top of the lower isomeric state in ^{152}Ho or ^{153}Er.

in fig. 2. Previously known low-spin isomers were observed in ^{145}Sm, ^{144,145,147}Eu, ^{148}Gd, ^{155,157}Er and ^{161}Yb. New low-spin isomeric states are observed with half-lives of 13 ± 2 and > 200 ns, which are assigned to ^{156}Ho or ^{155}Ho and ^{159}Yb, respectively. A third low-spin isomer is located in ^{151}Er, or less likely in ^{151}Ho, with $t_{1/2}$ = 40 ± 20 ns, $\bar{M}_D$ = 3.0 ± 1.0 and E_X = 2.5 + 0.7 MeV. An isomer at E_X = 1006 keV in ^{148}Tb was found with $t_{1/2}$ = 23 + 3 ns.

Several previously known high-spin isomers were seen in ^{146,147}Gd, ^{148,149}Dy, ^{152}Dy and ^{154}Er, already quoted. The properties of the new high-spin isomers, as measured in this experiment, are summarized in table 1. They all occur in nuclei with at most four neutrons outside the closed N = 82 shell and four protons outside the semi-closed Z = 64 shell. All these isomers, characterized by half-lives in the range of 15 to 500 ns have excitations energies between 3 and 7 MeV, multiplicities up to 12 and estimates spins to $I \approx 30$. In ^{149}Dy a new isomer with a very high spin between 47/2 and 63/2 is located at E_X = 6.9 ± 0.8 MeV. Evidence is found that the $I^\pi = 27/2^-$ isomer at E_X = 2.66 MeV is fed by γ-rays deexciting the new isomer. The excitation energy of the pres-

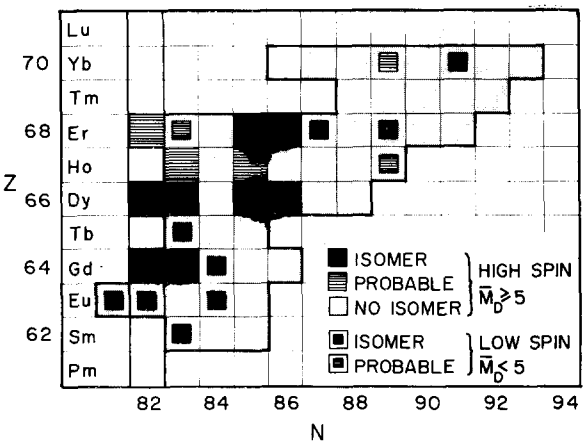

Fig. 2. The region of studied final nuclei, in which the observed low-spin isomeric states are indicated separately. Nuclei in which no high-spin isomers were found with $t_{1/2} > 5$ ns are also indicated. For the relation between the delayed multiplicity and spin see text.

ently located isomer in ^{149}Dy is comparable to the one reported [9] in ^{147}Gd at E_x = 7.5 MeV with $I < 49/2$. The similarity in nuclear structure between these two nuclei indicated by the properties of the low-lying levels including the $I^\pi = 27/2^-$ isomeric state, seems now also to extend to high ($\approx$ 7 MeV) excitation energy. Another interesting pair of isotones differing by two protons is ^{151}Dy and ^{153}Er. In ^{151}Dy an isomer is found at $E_x = 6.2 \pm 0.6$ MeV. In ^{153}Er at least one isomer is identified, a second one may occur at $E_x = 6.0 \pm 1.0$ MeV, although the deexciting γ-rays might as well belong to the decay of an isomer in ^{152}Ho. Very recent results of detailed spectroscopic studies [12] on ^{151}Dy confirm the present findings. Two isomers are observed in the reaction ^{144}Sm + 120 MeV ^{12}C, belonging to ^{150}Ho and/or ^{150}Er. Unfortunately it was impossible to distinguish between the case that the delayed cascades stand on top of each other in one of the nuclei and the case that isomers are present in both nuclei. During the course of this work similar results were also obtained by the extended Copenhagen–Darmstadt collaboration utilizing a sum spectrometer and various heavy-ion beams [10].

In conclusion it is important to note that the obseved high-spin isomers are located near the $N = 82$ closed neutron shell and the $Z = 64$ semi-closed proton shell. Of almost equal importance is the absence of high-spin isomeric states further away from these closed shells. These facts and the observed spin upper limit of $I \lesssim 30$ indicate that the presently located high-spin isomers belong to the first category, as defined above. No isomers of the second category with spins $I > 40$ have been observed in the present experiments.

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